Observations of wave activity in the ionosphere over South Africa in geomagnetically quiet and disturbed periods

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Abstract

The present paper deals with observations of wave activity in the period range 1–60 min at ionospheric heights over the Western Cape, South Africa from May 2010 to July 2010. The study is based on the Doppler type sounding of the ionosphere. The Doppler frequency shift measurements are supplemented with measurements of collocated Digisonde DPS-4D at SANSA Space Sciences, Hermanus. Nine geomagnetically quiet days and nine geomagnetically active days were included in the study. Waves of periods 4–30 min were observed during the daytime independent of the level of geomagnetic activity. Amplitudes of 10–30 min waves always increased between 14:00 and 16:15 UT (16:00–18:15 LT). Secondary maxima were observed between 06:00 and 07:00 UT (08:00–09:00 LT). The maximum wave amplitudes occurred close to the time of passage of the solar terminator in the studied region which is known to act as a source of gravity waves.

Waves of periods 30–50 min were observed in the F2 layer during the daytime on five out of the eighteen days analysed, on four geomagnetically active days and on one quiet day. On the geomagnetically active day of 27 July 2010, waves of periods 1–2.5 min occurred in the evening and night hours. These waves appeared simultaneously with 1–2.5 min fluctuations of horizontal components of the local geomagnetic field. We suppose that the 1–2.5 min ionospheric oscillations are a response to the geomagnetic micropulsations.

Keywords: Waves in the ionosphere; HF Doppler type sounding; Geomagnetic activity

1. Introduction

The state of ionization and dynamics of the ionosphere is mainly influenced by the Sun. The degree of ionization is determined by the flux of ionizing radiation together with the temperature and chemical composition of the upper atmosphere and plasma transport. Increased solar activity and consequent disturbances of the geomagnetic field may result in disturbances of the ionosphere due to electromagnetic coupling between the ionosphere, magnetosphere, and solar wind and due to changes in circulation patterns in the upper atmosphere.

The processes occurring in auroral zones are considered as a source of gravity waves. Gravity waves are generated here in geomagnetically disturbed as well as in quiet periods (e.g. Hajkowicz, 1991; Bowman, 1992; Williams et al., 1988; Oya et al., 1982; Oyama et al., 2001; Ogawa et al., 2009; Kelley, 2011). Model results of Mayr et al. (1990) showed that the wave amplitudes are not simply directly related to...
Hocke and Schlegel (1996) distinguish two types of gravity waves generated in auroral zones and their ionospheric manifestation – traveling ionospheric disturbances (TIDs): large-scale TIDs propagate in the upper atmosphere with velocities close to the thermospheric speed of sound and have periods of about 30 min to 3 h and horizontal wavelength more than 1000 km. Medium-scale TIDs have periods of about 15–60 min and horizontal wavelength of the order of hundreds of km. The medium-scale waves travel in the lower atmosphere with velocities lower than the local sound speed before they get into the upper atmosphere. The existence of various sources of gravity waves in the lower atmosphere makes it difficult to prove whether the observed medium scale TID was generated in auroral thermosphere.

Studies concur that the variability of the ionospheric F2 layer cannot be merely explained by latitudinal and seasonal factors or by geomagnetic activity and that there exists some influence of processes in the lower atmosphere (e.g. Kazimirovsky and Kokourov, 1995; Forbes et al., 2000; Rishbeth and Mendillo, 2001; Sauli and Boska, 2001; Rishbeth 2006). Waves of various time and spatial scales are generated by these processes and transfer the energy from the lower atmosphere to ionospheric heights. The waves modify turbulent mixing, temperature, and wind in the thermosphere, influence conductivity in the E region and contribute to the generation of electric fields through dynamo mechanisms. Through the mentioned mechanisms waves influence the ionosphere (Forbes et al., 2000).

When studying the ionosphere over South Africa, the possible influence of the South Atlantic Magnetic Anomaly (SAMA) should be considered. Weak magnetic field in the region between South America and Southern Africa enables energetic particles from the magnetosphere to enter deep into the atmosphere. The precipitating particles act as a source of extra ionization, and the effect in the E region and contribute to the generation of electric fields through dynamo mechanisms. Through the mentioned mechanisms waves influence the ionosphere (Forbes et al., 2000).

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The measurements were done in South Africa in the Western Cape province. We performed continuous high frequency Doppler type sounding to observe wave activity in the ionosphere. The height of observations was estimated from measurements of the collocated Digisonde DPS-4D at SANSA Space Sciences, Hermanus (34°25’S, 19°13’E) (Reinisch et al., 2005). The Digisonde measurements are conducted every 15 min. Geomagnetic activity was evaluated using global geomagnetic indices Kp and Dst (progress of geomagnetic storms). AE index was also taken in account since it represents activity of auroral electrojets and geomagnetic substorms at high latitudes. The AE index is determined from measurements of twelve geomagnetic observatories around the auroral oval in the Northern Hemisphere. However, Ballatore et al. (1998) suggest that Northern and Southern Hemisphere AE indices should be similar due to conjugated auroral zones. Data from Hermanus Magnetic Observatory were employed in evaluation of fluctuations of the local geomagnetic field.

The Doppler type sounding technique of the ionosphere is based on the measurements of frequency shift between a transmitted radio wave of a constant frequency of 3.59 MHz and the received wave after reflection from the ionosphere. This sounding technique enables observations of ionospheric fluctuations down to periods of tens of seconds. The South African Doppler sounding system was developed at the Institute of Atmospheric Physics, Prague, Czech Republic (IAP) and is of the same type as the system operating since 2004 in the Czech Republic. A short description of the system is given in Chum et al. (2010) and references therein. The Doppler sounding system in South Africa was installed in May 2010 (Fig. 1). It consists of three transmitters and one receiver, which, therefore,
provides three different sounding paths. The transmitters are located in Worcester (33°39′S, 19°25′E), Cape Town (33°56′S, 18°28′E), and Arniston (34°38′S, 20°13′E). The frequencies of the transmitters are mutually shifted by 4 Hz, therefore a single receiver located at SANSA Space Sciences, Hermanus (34°25′S, 19°13′E) can be used for...
reception of all three signals. The measuring paths Cape Town–Hermanus and Arniston–Hermanus follow the coast, the transmitter in Worcester is located beyond a mountain ridge. The Doppler sounding systems have been used for statistical investigation into horizontal propagation of gravity waves over Europe and South Africa (Chum et al., 2012).

The received signal is digitized and Doppler shift spectrograms of the power spectral densities of the received signal are computed (an example of the Doppler shift spectrogram can be seen in Fig. 2). For more details see Chum...
et al. (2010). We used Doppler shift as a single valued function of time for individual sounding paths to perform a spectral analysis of the observed waves. To obtain these functions we search for the maximum power spectral density on each sounding path at each point on the time axis of the Doppler shift spectrogram. The fit procedure is done automatically and the fitted curve is then manually checked. These functions are obtained reliably only in the intervals in which a distinct single trace is seen in the Doppler shift spectrograms for each sounding path. In the case where there are multiple traces of similar intensity or a spread of the signal, the reliability of the fit is low and these intervals are not used in further calculations.

We applied a continuous wavelet transform based on the complex Morlet wavelet to get information about the spectral content of the signal and how it changes with time. We studied wave activity in the period range 1–60 min and focused on an existence of period bands with permanently high and to the contrary low wave activity in the studied region.

Based on the findings of the visual inspection of the waveletograms, we analysed in more detail wave activity in the period range of 1–30 min. We established the so-called regional Doppler shift coefficients (regional DSC) for this purpose. The regional DSC is a qualitative indicator of diurnal changes of wave activity, and was obtained as follows: First, we divided the interval 1–30 min into six subintervals of five minute width (four minute width for the first subinterval). Then, the Doppler shift coefficients were calculated for each measuring path as the arithmetic means of amplitudes of the complex wavelet transform coefficients in the considered period ranges for all time steps. The Doppler shift coefficients represent proxies for typical spectral amplitudes for the given sounding path in the individual period (frequency) ranges. Finally, the daily regional DSC was computed as an average of Doppler shift coefficients from all the available sounding paths in the considered subintervals. The plots of maxima, minima, and median of daily regional DSCs represent the diurnal variation of wave activity for the individual period ranges in the group of geomagnetically quiet days (Fig. 3) and geomagnetically active days (Fig. 4). The sections in the cone of influence (an area of the computed wavelet scalogram where the edge effects play an important role, so

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**Fig. 5.** Kp indices on geomagnetically quiet days included in the study.
this area should not be taken into account) were removed according to Torrence and Compo (1998).

We analysed measurements on nine geomagnetically quiet days and on nine geomagnetically active days according to Kp index in the time interval from 25 May to 21 July 2010, it means in the time interval around winter solstice in the Southern Hemisphere. In the group of geomagnetically quiet days, we also checked whether there are any distinct peaks in the AE index pointing to sudden increase of the activity of auroral electrojets. Such days were not included in the group of geomagnetically quiet days. The Kp index plots on individual days are given in Figs. 5 and 6.

In the time intervals when series of short period ionospheric waves occurred (periods around 1–3 min), we searched for corresponding wave patterns in records of local geomagnetic field and its horizontal and vertical components. Geomagnetic micropulsations may cause ionospheric response in the form of oscillations which have the same period as the micropulsations and occur simultaneously with the micropulsations (Marshall and Menk, 1999; Chum et al., 2009). The magnetometer records at Hermanus Magnetic Observatory (34°25'S, 19°13'E) are sampled with period 5 s and include data of horizontal and vertical components and the amplitude of the local geomagnetic field. First, we estimated the wave spectra in ionospheric and geomagnetic records using wavelet transform (based on complex Morlet mother wavelet) and we compared the wave periods and the time of occurrence. After that, we drew a comparison of the filtered ionospheric signal and the filtered geomagnetic records. We used high pass Butterworth filter, the cut-off period was estimated according to the spectra shown by the wavelet transform. In the case we found simultaneous occurrence of waves in the ionospheric and geomagnetic records with the same spectra, we assumed the ionospheric oscillations are related with geomagnetic micropulsations.

3. Results

We studied wave activity at ionospheric heights in South Africa in the time interval from 25 May 2010 to 21 July 2010, which is around winter solstice in the Southern Hemisphere. The level of geomagnetic activity represented

![Fig. 6. Kp indices on geomagnetically active days included in the study.](image-url)
by Kp, Dst, and AE indices was considered. We focused on waves in the period range of 1–60 min.

### 3.1. Wave activity on geomagnetically quiet and active days

We compared the level of wave activity on days with disturbed geomagnetic field with that on geomagnetically quiet days. The term wave activity refers to the occurrence of waves of particular periods, the duration of wave activity in a particular period range, and the amplitudes of waves.

Tables 1 and 2 summarize occurrence of waves in the period range 1–50 min on geomagnetically active and quiet days, respectively. Wave activity in the period range 50–60 min was low on the studied days. Waves of periods between 30 and 50 min were observed on four geomagnetically active days (of nine studied ones) and on one geomagnetically quiet day (of nine studied ones). Waves of periods from 4 to 30 min occurred on both geomagnetically quiet and active days.

On 29–31 May 2010, there was a moderate geomagnetic storm in progress; main phase of the storm occurred on 29 May 2010 with Dst = \(-85\) nT at 13:00–14:00 UT (15:00–16:00 LT). During the day of 29 May 2010, a wave of period around 45 min was observed on the sounding paths Worcester–Hermanus and Cape Town–Hermanus between 14:05 and 14:55 UT (16:05–16:55 LT) (Fig. 7). The 3.59 MHz radio wave reflected at heights 167–192 km (Fig. 8). Transmitted signal when reflected in the ionospheric plasma is split into two modes, ordinary and extraordinary mode. Critical frequencies of ionospheric layers are denoted as fo or fx (f stands for frequency and o or x stand for ordinary or extraordinary mode, respectively) and name of the layer (e.g. foE means critical frequency of the E layer measured using the ordinary mode, fxF1 means critical frequency of the F1 layer measured using the extraordinary mode). The Doppler system sounding frequency of 3.59 MHz was close to fxF1 between 13:45 and 14:00 UT (15:45 and 16:00 LT) which might have influenced the Doppler shift measurements. The fxF1 was 3.78 MHz at 13:45 UT (15:45 LT) and the F1 layer disappeared before 14:00 UT (16:00 LT). After 14:00 UT (16:00 LT), the 3.59 MHz radio wave reflected from the F2 layer. Critical frequencies foE were 2.02–2.2 MHz and foF2 were 6.00–7.00 MHz. The F1 layer reappeared at 15:00 UT (17:00 LT) with critical frequency, foF1 = 2.60 MHz. It is difficult to decide whether the observed Doppler shift between 13:45 and 14:00 UT (15:45 and 16:00 LT) is a consequence of vertical movement of the reflecting layer or it is related with the occurrence of F1 layer. We assume that the observed Doppler frequency shift between 14:05 and 14:55 UT (16:05–16:55 LT) was caused by vertical motions of the reflecting layer. The measurements at the path Arniston–Hermanus were not evaluated due to a gap in the data.

### Table 1

Summary of observations of wave activity in the period range 1–50 min on geomagnetically active days. The filled box means, waves of corresponding period were observed on the day.

<table>
<thead>
<tr>
<th>Period [min]</th>
<th>01-02</th>
<th>02-04</th>
<th>04-06</th>
<th>06-08</th>
<th>08-10</th>
<th>11-15</th>
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<th>21-25</th>
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<th>31-35</th>
<th>36-40</th>
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Table 2
Summary of observations of wave activity in the period range 1–50 min on geomagnetically quiet days. The filled box means, waves of corresponding period were observed on the day.

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<tr>
<th>Period [min]</th>
<th>01-02</th>
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Fig. 7. 29 May 2010, 13:30–15:30 UT (15:30–17:30 LT). The Doppler records at sounding paths; Cape Town–Hermanus and Worcester–Hermanus. Periods shorter than 30 min are filtered. Note the y-axis is reversed.
On 31 May 2010, 30–40 min waves occurred on all sounding paths between 15:10 and 15:50 UT (17:10–17:50 LT) (Fig. 9). The 3.59 MHz radio wave reflected from the F2 layer. The F1 layer has not been developed in the study.

Fig. 8. Reflection heights of the 3.59 MHz on 29 May 2010, 13:30–15:30 UT (15:30–17:30 LT). Dashed line shows virtual height of reflection of the extraordinary wave, dash-dot line virtual height of reflection of the ordinary wave. Solid line shows true reflection height from the profile. Manually checked ionograms were used.

Fig. 9. 31 May 2010, 15:00–16:30 UT (17:00–18:30 LT). Doppler records at sounding paths; Cape Town–Hermanus, Worcester–Hermanus, and Arniston–Hermanus. Periods shorter than 30 min are filtered. Note the y-axis is reversed.
ied time interval 15:00–16:30 UT (17:00–18:30 LT). The reflection heights of the 3.59 MHz radio wave are shown in Fig. 10. We assume, the large positive Doppler shift after 16:00 UT (18:00 LT) is related with changes of electron concentration in the ionosphere. Critical frequencies foE and foF2 are shown in Fig. 11.

Summary of the observations of 30–50 min waves is given in Table 3. The table indicates the group into which each of the listed days belongs according to the level of geomagnetic activity. Approximate period, time of occurrence, and height of observation (true height of reflection of the 3.59 MHz radio wave) are given. Peak to peak amplitude of the Doppler frequency shift is assumed to be proportional to the amplitude of the passing wave.

Table 3
Summary of observations of 30–50 min waves.

<table>
<thead>
<tr>
<th>Day</th>
<th>Geomagnetic activity</th>
<th>Wave period</th>
<th>Time of observation (UT)</th>
<th>True reflection height of the 3.59 MHz wave</th>
<th>Maximum peak to peak amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>29 May 2010</td>
<td>Active day</td>
<td>40–50 min</td>
<td>14:05–14:55</td>
<td>167–192 km</td>
<td>0.22 Hz</td>
</tr>
<tr>
<td>31 May 2010</td>
<td>Active day</td>
<td>30–40 min</td>
<td>15:10–15:50</td>
<td>179–223 km</td>
<td>0.27 Hz</td>
</tr>
<tr>
<td>03 June 2010</td>
<td>Active day</td>
<td>40 min</td>
<td>06:50–08:50</td>
<td>159–174 km</td>
<td>0.10 Hz</td>
</tr>
<tr>
<td>30 June 2010</td>
<td>Active day</td>
<td>30–40 min</td>
<td>13:50–14:45</td>
<td>166–179 km</td>
<td>0.08 Hz</td>
</tr>
<tr>
<td>08 June 2010</td>
<td>Quiet day</td>
<td>40–45 min</td>
<td>14:40–15:30</td>
<td>171–192 km</td>
<td>0.25 Hz</td>
</tr>
</tbody>
</table>

Figs. 3 and 4 show medians, maxima, and minima of regional Doppler shift coefficients separately for geomagnetically quiet days and for geomagnetically active days in the period bands 1–5 min, 5–10 min, 10–15 min, 15–20 min, 20–25 min, and 25–30 min. Diurnal variability of wave activity can be seen in the plots. Maximum wave amplitudes occurred on both geomagnetically quiet and active days between about 14:00 and 16:15 UT (16:00–18:15 LT) in the period bands from 10 to 30 min. Comparing the plots of Doppler shift coefficients with the wavelet transform spectrograms, we confirmed that these maxima are related with superimposed waves of different periods. A secondary maximum occurred between 06:00 and 07:00 UT (08:00–09:00 LT) in the period bands between 10 and 30 min on geomagnetically active days. On geomagnetically quiet days, the morning maximum was registered on less than half of the days.

According to model results of Vadas (2007), small and medium scale gravity waves (periods shorter than 60 min, wavelengths shorter than 500 km, and phase velocities...
lower than 100 m s\(^{-1}\)) coming into the thermosphere from lower atmosphere dissipate at altitudes 150–250 km. These altitudes correspond to altitudes at which the increased wave activity in the period range 10–30 min was observed in our measurements. It may indicate that the observed waves do not originate in the lower atmosphere.

Fig. 12. Waves of periods 1–2.5 min were observed on the geomagnetically active day of 27 June 2010 at 20:02–20:08 UT (22:02–22:08 LT) and at 20:14–20:17 UT (22:14–22:17 LT). A record from the measuring path Worcester–Hermanus is shown. Top panel: wavelet transform of the signal, black line represents cone of influence. Bottom panel filtered signal, periods longer than 3.5 min are filtered.

Fig. 13. Waves of periods 1–2.5 min observed on the geomagnetically active day of 27 June 2010 at 23:03–23:15 UT (01:03–01:15 LT on 28 June 2010). A record from the measuring path Cape Town–Hermanus is shown. Top panel: wavelet transform of the signal. Bottom panel filtered signal, periods longer than 3.5 min are filtered.
The largest wave amplitudes occurred around the time of passage of the solar terminator in the studied region. The time of passage of the morning terminator in the studied region at winter solstice is about 05:51 UT (07:51 LT).
LT) at the ground and 04:36 UT (06:36 LT) at heights 200 km; time of passage of the evening terminator is about 15:33 UT (17:33 LT) at the ground and 16:47 UT (18:47 LT) at heights 200 km. Solar terminator is known to act as a source of gravity waves (e.g. Somsikov and Ganguly, 1995) and shall be therefore also considered as a possible cause of the increased wave activity around 16:00 UT (18:00 LT) and around 06:00 UT (08:00 LT).

It should be noted that there was not a continuous reception of the Doppler signal from about 16:15–16:30 UT (18:15–18:30 LT) to about 05:30–05:45 UT (07:30–07:45 LT). Signal loss occurred each evening which was mostly due to a low F2 critical frequency; i.e. foF2 and fxF2 were lower than the sounding frequency of 3.59 MHz.

3.2. Ionospheric response to geomagnetic micropulsations

Series of short period waves occurred on 27 June 2010 at 20:02–20:08 UT (22:02–22:08 LT), 20:14–20:17 UT (22:14–22:17 LT) and at 23:03–23:15 UT (01:03–01:15 LT on 28 June 2010) (Figs. 12 and 13). The wave periods were around 1–2.5 min. As reported e.g. by Marshall and Menk (1999) and Chum et al. (2009), the short period ionospheric oscillations may be caused by micropulsations of the local geomagnetic field. We therefore compared the spectra and the time of occurrence of the ionospheric waves with those of fluctuations of the local geomagnetic field components. We found simultaneous occurrence of ionospheric waves and oscillations of the north–south and east–west components of the local geomagnetic field (Figs. 14 and 15).

The critical frequency of the F2 layer was close to the Doppler sounding frequency 3.59 MHz in both time intervals when the 1–2.5 min ionospheric waves occurred. At 20:00–20:15 UT (22:00–22:15 LT), foF2 was around 3.4 MHz and fxF2 was 3.72–3.8 MHz. At 23:00–23:15 UT (01:00–01:15 LT on 28 June 2010), foF2 was 3.23 MHz and fxF2 was 3.58–3.60 MHz. As the foF2 was lower than the Doppler system sounding frequency, it is obvious that we observed the ionospheric effects of geomagnetic micropulsations on the extraordinary wave. Any other event of night time occurrence of short period ionospheric waves was not found because there was either a spread of signal which disabled observations of small scale phenomena on 29 May, 3 June, and 8 June 2010 or the Doppler sounding signal was not received due to low foF2 and fxF2 (on the rest of analysed days).

Similar short period oscillations in the Doppler records were also observed in the morning immediately after the start-up of the signal reception following the night time signal loss on 27 June 2010 (Fig. 2), the other geomagnetically active day of 17 June 2010 and on geomagnetically quiet days of 8 June 2010 and 10 July 2010. The periods of the waves were estimated to be around 1–3 min. It is obvious that the critical frequency of the F2 layer was close to the frequency of the Doppler sounding wave during the time interval of the morning start-up of the signal reception and thus ionospheric response to geomagnetic pulsations can be noticeable. Ionograms from the Digisonde at SANSA Space Science, Hermanus were checked to obtain accurate values of critical frequencies. The amplitudes of fluctuations of the local geomagnetic field on the above mentioned days were mostly between 0.1 and 0.3 nT, except of 17 July 2010 when the vertical component fluctuated with amplitudes up to 0.4 nT. On 8 June 2010, ionospheric oscillations detected on the sounding path Worcester–Hermanus occurred together with fluctuations of the north–south component of the local geomagnetic field at about 05:54–05:56 UT (07:54–07:56 LT). On 27 June 2010, ionospheric oscillation on sounding paths Worcester–Hermanus and Arniston–Hermanus were observed at the same time as fluctuations of both horizontal components of the local geomagnetic field. Records on the other sounding paths were not compared with geomagnetic records because amplitudes of ionospheric oscillations were too small to capture them properly in the fitting procedure of the Doppler shift function on time. For the same reason the comparison of Doppler shift records and geomagnetic records was not done on 17 June and 10 July 2010.

4. Summary

We studied wave activity at ionospheric heights under different levels of geomagnetic activity over South Africa during the period 25 May–21 July 2010; it means in local winter. We focused on the period range 1–60 min, which includes periods of infrasound and gravity waves and ionospheric oscillations caused by geomagnetic micropulsations.

A clear diurnal variability was found for waves of periods 10–30 min. The lowest wave amplitudes were observed before midday, maxima occurred always between 14:00 and 16:15 UT (16:00–18:15 LT), secondary maxima occurred on geomagnetically active days at 06:00–07:00 UT (08:00–09:00 LT). The maximum wave amplitudes occurred close to the time of passage of the solar terminator in the studied region.

Waves of periods between 30 and 50 min were observed on four geomagnetically active days (of nine studied) and on one geomagnetically quiet day (of nine studied). The waves were observed at all Doppler sounding paths, persisted for one wave cycle and their amplitudes were lower than amplitudes of 10–30 min waves.

On the geomagnetically active day of 27 June 2010, 1–2.5 min waves occurred at 20:02–20:08 UT (22:02–22:08 LT), 20:14–20:17 UT (22:14–22:17 LT), and at 23:03–23:15 UT (01:03–01:15 LT on 28 June 2010). We assume, these short period ionospheric waves were related with geomagnetic micropulsations, since 1–2.5 min fluctuations of the horizontal components of the local geomagnetic field were observed together with the 1–2.5 min ionospheric waves.

A limited number of cases have been presented here, and, therefore, this study cannot be considered conclusive.
We believe, however, that this study does provide a starting point towards an improved understanding of wave activity in the ionosphere above South Africa.

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References


